

Geomorphic and stream flow influences on large wood dynamics and displacement lengths in high gradient mountain streams (Chile)

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Abstract:

Understanding large wood (LW, ≥ 1 m long and ≥ 10 cm in diameter) dynamics in rivers is critical for many disciplines including those assessing flood hazard and risk. However, our understanding of wood entrainment and deposition is still limited, mainly because of the lack of long-term monitoring of wood related processes. The dataset presented here was obtained from more than 8 years of monitoring of 1264-tagged wood pieces placed in four low-order streams of the Chilean mountain ranges, and is used to further our understanding of key factors controlling LW dynamics. We show that LW displacement lengths were longer during periods when peak-flow water depths (H_{\max}) exceeded the bankfull stage (H_{Bk}) than in periods with $H_{\max} \leq H_{Bk}$, and that these differences were significantly higher for smaller wood pieces. LW length and length relative to channel dimensions were the main factors governing LW entrainment; LW displacement lengths were inversely related to the ratio of piece length to $H_{15\%}$ (i.e. the level above which the flow remains for 15% of the time) and to the ratio of $H_{15\%}$ to bankfull width. Unrooted logs and LW pieces located at the bankfull stage travelled significantly longer distances than logs with attached rootwads and those located in other positions within the bankfull channel. A few large logjams were broken during the period of observation, and in all occasions, LW from these broken logjams did not travel over longer distances than other pieces of LW moved in the same periods and in the same stream segments. Most importantly, our work reveals that LW dynamics tend to be concentrated within a few reaches in each stream and that reaches exhibiting high wood dynamics (extensive entrainment, deposition or repositioning of LW) are significantly wider and less steep than less dynamic reaches.

KEY WORDS Large wood dynamics; Displacement length; Channel morphology; Mountain streams

1 INTRODUCTION

Understanding large wood (hereafter referred to as LW, i.e., wood pieces at least 1 m in length, and at least 10 cm in diameter) dynamics in rivers is critical for many disciplines including those addressing flood hazard and risk assessments. Moreover, the geomorphic (Robison & Beschta, 1990; Beechie & Sibley, 1997; Chen et al., 2008) and ecological (Diez et al., 2001; Chen et al., 2008; Vera et al., 2014) significance of LW on stream ecosystems is widely recognized. LW is a key component of river systems, and although LW removal from stream channels has been a very common management strategy during past centuries (Wohl, 2014), this paradigm is now changing in such a way that wood is often reintroduced to watercourses as a river restoration technique (Kail, 2003; Buxton, 2010; Roni et al., 2015). However, during extreme floods, when large quantities of wood can be transported, LW clearly has the potential to clog or even collapse bridges and other in-channel infrastructure (Rickli, 2009; Badoux et al., 2015; Lucía et al., 2015). In addition, the transport of LW can cause breakdown of temporary wood dams that in turn might trigger sudden sediment and LW surges (Rickenmann & Koschni, 2010; Wohl, 2011). In such situations, the presence of LW and its recruitment and transport can indeed increase flood hazards (Daniels & Rhoads, 2003; Ruiz-Villanueva et al., 2013).

Consequently, to take advantage of the benefits of LW and to prevent its potential negative impacts in the case of floods, natural LW dynamics must be managed properly (Mao et al., 2013; Wohl et al., 2016; Mazzorana et al., 2017). However, our understanding of wood entrainment and deposition processes is still limited (Schenk et al., 2014; Dixon & Sear, 2014) and largely restricted to a small number of field-based (Ravazzolo et al., 2015), laboratory (Welber et al., 2013) or modelling (Ruiz-Villanueva et al., 2016a) approaches, typically hampered by short measurement periods and a limited number of tagged logs. Therefore, a better understanding of geomorphic and stream flow influences on LW

dynamics, and tools for the quantification of displacement lengths and entrainment and deposition processes are still needed and are a prerequisite for proper management of wood transport volumes and related hazards. In particular, the analysis of factors controlling LW dynamics and displacement lengths in different environments might be extremely useful. We know that LW dynamics are highly dependent on channel slope (Gurnell et al., 2002; Merten et al., 2010; Iroumé et al., 2014), and that LW deposition mainly occurs in wider channels with gentle gradients (Iroumé et al., 2015; Wyżga et al., 2015; Ruiz-Villanueva et al., 2016a), but recent work has started to look into LW dynamics and residence times of LW pieces in smaller, and much steeper, headwater catchments (Jochner et al., 2015; Galia et al., 2017). In addition, it is widely acknowledged that LW mobility is inversely proportional to the complexity of the channel pattern, as transport capacity is usually lower in multithread than in single thread channels (Wyżga et al., 2015; Ruiz-Villanueva et al., 2016b).

The dimensions of wood pieces relative to bankfull channel width and depth also control LW transport potential (Gurnell et al., 2002; Wohl & Cadol, 2011; Wohl, 2011). General trends suggest that LW length is a main factor governing LW transport in single thread and narrow channels, whereas wood diameter may control LW movement in multithread and wide channels (Welber et al., 2013; Ruiz-Villanueva et al., 2016b). Larger piece diameters require higher flow depths to be entrained and transported, thereby influencing displacement distance (Braudrick & Grant, 2000; Welber et al., 2013; Bertoldi et al., 2014). LW moves farther and more frequently in large streams (>5th order) than small ones (Bilby, 1985; Lienkaemper & Swanson, 1987; Bilby & Ward, 1989, 1991; Martin and Benda, 2001) and smaller pieces move farther than larger pieces (Lienkaemper & Swanson, 1987; Young, 1994). Martin & Benda (2001) report that in narrow (about 3-5 m wide) channels, the probability of a LW piece being transported at least 50 m is 90%, but only 10% of the pieces would, at the same time, move more than 300 m, whereas in 20–30 m wide channels, LW is likely to travel at

least 300 m with a 90% probability. However, the displacement distance of a LW piece is significantly related to other factors, such as branching complexity, wood type and decay (i.e., density); and this renders the process highly variable and also difficult to predict (Dixon & Sear, 2014). Moreover, LW is routed more quickly and stored for less time in confined reaches, but mobility and displacement lengths are limited during low flows by coarse substrate and other obstructions (Kramer & Wohl, 2016). However, the breaking of logjams may create a pulse of transport and individual LW pieces from these jams can be transported several kilometers downstream (Wohl, 2011). Pieces tend to stop when the water depth of the segment at peak flow is lower than the diameters of the LW pieces (Abbe et al., 1993; Haga et al., 2002), but the location of stable or recurring LW jams reduces LW displacement distances for wood of all sizes (Braudrick & Grant, 2001; Haga et al., 2002; Warren & Kraft, 2008; Jochner et al., 2015). Hydrodynamics play a significant role as well because flood magnitude and duration may control LW transfer (Ruiz-Villanueva et al., 2016c), but to test this hypothesis, *in-situ* observations are needed during floods (Wyżga et al., 2017).

Long term observations of LW transport are rarely found in the scientific literature, and new techniques (e.g., video and time-lapse photographic monitoring and tracking) have been introduced only recently to address this issue (MacVicar et al., 2009; MacVicar & Piégay 2012; Dixon & Sear, 2014; Kramer & Wohl, 2014; Ravazzollo et al., 2015; Boivin et al., 2016; Piégay et al., 2017). One exception to this general lack of information is the database compiled in four low-order mountain streams located in southern Chile, where monitoring of LW dynamics has been conducted systematically since the end of 2008 (Iroumé et al., 2015). This database is built upon LW surveys using more than 1260 tagged LW pieces and therefore allows one to address several key issues related to wood dynamics during different flow conditions. In previous studies, Iroumé et al. (2015) analyzed factors controlling the ratio of wood mobility (i.e., the proportion of tagged LW that moved). Results confirmed that

piece size controls wood mobility and that transport ratios in these southern Chilean streams were relatively low as compared to other mountain streams. Although Iroumé et al. (2015) observed that certain river reaches concentrated most of the wood dynamics, they did not attribute this to any specific factor. Here, we further mine and expand the database to fill this particular research gap. This study focused on (a) the identification of flow and wood characteristics in controlling large wood mobility (i.e., in terms of wood entrainment and displacement lengths, deposition and repositioning) for the 8-year period from 2009-2016, and (b) examining geomorphic characteristics of channel reaches that exhibit high wood dynamics (extensive entrainment, deposition, or repositioning of LW during floods). This work is to our knowledge, unique in terms of the period of observation (i.e., 8 years), the spatial scale of analysis (i.e., four streams, and 67 reaches with a total channel length of 6.8 km), the number of wood pieces monitored (i.e., 1264), and the ability to quantify reach characteristics that drive LW dynamics.

2 STUDY SITES

The study sites are channel segments of four third-order streams located in the Coastal and Andes mountain ranges in southern Chile: one segment (1004 m long) of the Pichún stream (drainage area of 431 ha and located in the eastern aspect slopes of the Coastal mountain range); a 2188-m segment of the El Toro stream (drainage area of 1783 ha and located in the Malleco Forest National Reserve in the Andes mountain range); a 2070-m reach of the Tres Arroyos stream (drainage area of 907 ha and in Malalcahuello–Nalcas Forest National Reserve in the Andes mountain range); and one segment, 1557 m in length, of the Vuelta de Zorra stream (drainage area of 587 ha located in the Valdivian Coastal Reserve) (Figure 1). Extensive descriptions of these sites are presented in Andreoli et al. (2007, 2008), Comiti et al. (2008), Iroumé et al. (2010, 2011, 2014, 2015) and Ulloa et al. (2011).

FIGURE 1

Mean bankfull channel widths of the study sites are 5 m in Pichún, 13 m in El Toro, 10 m in Tres Arroyos, and 11 m in Vuelta de Zorra, and mean bankfull depths vary between 0.8 m and 1.7 m (i.e. 0.8 m in Pichún; 1.7 m in El Toro; 1.1 m in Tres Arroyos; 1.0 m in Vuelta de Zorra). The Tres Arroyos and Pichún study segments are the steepest with a mean slope equal to $0.1 \text{ m} \cdot \text{m}^{-1}$, El Toro and Vuelta de Zorra have a mean segment slope of 0.05 and $0.04 \text{ m} \cdot \text{m}^{-1}$, respectively.

We used the well-known Montgomery & Buffington (1997) classification system to describe channel morphologies. The Tres Arroyos channel is mainly straight along the entire segment and characterized by cascade and step-pool to pool-riffle type morphologies, with a high degree of forced morphologies associated with LW. El Toro has cascade to step-pool bed-forms without forced morphologies associated with LW. Pichún features a straight channel and step-pool and cascade morphologies caused mainly by the presence of large boulders, without wood-forced morphologies. Finally, Vuelta de Zorra has a low gradient straight channel in the upper and middle courses and sinuous in the lower course of the study segment, with plane-bed, step-pool and pool-riffle bed-forms with some morphologies locally forced by LW.

The four basins are densely forested (with a forest cover of 84% at Pichún, 88% at El Toro, 64% at Tres Arroyos and 75% at Vuelta de Zorra), although the El Toro forest cover was severely affected by a wildfire in 2002. Vegetation is generally composed of native forest (Tres Arroyos and Vuelta de Zorra), with presence of *Eucalyptus globulus* and *E. nitens* in Pichún and Vuelta de Zorra, respectively. The riparian forest along the Pichún stream network contains the exotic conifer *Pinus radiata* from previous plantation rotations.

Mean annual precipitation ranges from 1190 mm in Pichún to 3000 mm in El Toro (being 2500 mm and 2300 mm in Tres Arroyos and Vuelta de Zorra, respectively). The catchments have

pluvial regimes with mean annual runoff of 283 mm in Pichún (period 2009-2015), 3045 mm in El Toro (period 2009-2013), 2488 mm in Tres Arroyos (period 1999-2015), and 3659 mm in Vuelta de Zorra (period 2009-2015); snowfall sometimes occurs in the El Toro and Tres Arroyos basins. Mean monthly maximum runoff for the same periods is 24, 284, 207, and 297 mm in Pichún, El Toro, Tres Arroyos and Vuelta de Zorra, respectively, which occurs during the rainy austral winter months (i.e. in July or August).

3 MATERIALS AND METHODS

The study segments were first surveyed at individual reach scales (defined based on uniformity of slope, channel width or LW abundance) between November 2008 and March 2009. LW length and diameter were measured during these surveys, and wood pieces were classified according to species groups (i.e. broadleaved, conifer), type (i.e. log, log with attached rootwads, rootwads, full tree, branch), and position in the channel. Positions in the channel follow the description by Iroumé et al. (2010) which is an adaptation of a previous classification (Robison and Bechta, 1990): (1) in-bankfull channel pieces are all the LW lying below the water level at bankfull flow, but excluding log-steps which form a different class; (2) log-steps; (3) the bankfull line group are all wood pieces found on the channel banks at an elevation corresponding to the bankfull stage; (4) channel-spanning logs are LW spanning the channel at an elevation higher than bankfull stage; and (5) channel margin pieces are those located on the area adjacent to the bankfull channel but having part of their length within the bankfull channel. Pieces with more than 50% of their length on the streambanks were considered in the channel margin position. When a wood piece occupies different portions of the channel its prevailing location was assigned.

Reach and segment bankfull widths and lengths as well as longitudinal slopes were also measured and a summary of this information can be found in Iroumé et al. (2010, 2014,

2015). We re-surveyed each segment after consecutive rainy winter periods until the end of 2013 for El Toro and 2016 for the other streams. During the surveys, ~ 4020 wood pieces were measured and from these a total of 1264 LW pieces (i.e., ~31% of measured wood pieces) were tagged with up to five numbered metallic tags per wood piece (Iroumé et al., 2010, 2015). Tagged wood pieces were randomly selected but intended to represent the characteristics of the population of measured LW pieces; sample and population were not statistically different (non-parametric Kruskal-Wallis test, $p\text{-value} > 0.05$) in terms of LW dimensions (length, diameter) and position in the channel.

Our sample of ~ 4020 measured and 1264 tagged wood pieces in four streams comprising 67 reaches with a total channel length of 6.8 km (591 wood pieces measured, and 186 pieces tagged per km of channel) exceeds sample sizes suggested by Young et al. (2006) for estimating wood piece dimensions and loads with a reasonable error. These authors measured 7289 pieces of coarse wood in 29.1 km of channels (250 measured wood pieces per km).

During each additional survey, every single tagged LW piece that had moved downstream from its initial position was re-located and re-classified, and all additional LW pieces recruited from bank erosion or toppling were measured as well, classified, located, and tagged (Iroumé et al., 2015).

Flow information for each study period and stream was derived from the records of the gauging stations located in or near the downstream end of each study segment, in natural sections of the El Toro, Tres Arroyos, and Vuelta de Zorra streams, and in a rectangular concrete channel in the case of Pichún stream. Water levels (measured at 10–15-minute intervals using digital sensors with a resolution of ± 2 mm) have been recorded since 1997 in the Tres Arroyos, and since mid-2008 at the Pichún, El Toro, and Vuelta de Zorra streams; more details on the gauging stations, length and resolution of the flow records can be found in Iroumé et al. (2015).

We compared LW displacement lengths for periods during which maximum water depth (H_{\max}) was higher or lower than bankfull stage (H_{Bk}); H_{\max} and H_{Bk} were both measured relative to the thalweg at gauging stations within each stream, with H_{\max} determined from the water level sensor. The gages are in locations that are morphologically characteristic for each river (i.e., the gage depths and confinement values are generally representative of each river, thus not introducing much uncertainty in our analysis, even for the case of Pichún whose gage is in a manmade channel).

In addition, we examined relationships between LW displacement length as a dependent variable and (1) flow characteristics measured at the location of the gauging stations (H_{\max} the maximum water level; H_{Bk} the bankfull stage; H_{\max}/H_{Bk} ; $H_{X\%}$, the level above which the flow remains for X% of the time), (2) LW diameter (D_{LW}) and length (L_{LW}), (3) LW dimensions relative to mean reach bankfull width (L_{LW}/w_{Bk} , henceforth L^*) and depth (D_{LW}/d_{Bk} , henceforth D^*), where w_{Bk} and d_{Bk} are those of the reach in which the LW piece was positioned before entrainment, and (4) wood piece species group (i.e. broadleaved, conifer), type (i.e. log, log with attached rootwad, rootwad, full tree, branch), and position in the channel (i.e. bankfull line, log-step, in-bankfull channel, channel margin, channel-spanning log) during each annual period as independent variables. Specifically, we implemented multiple regression analyses using log-link gamma generalized linear models (GLM, Dobson, 1990; Hardin & Hilbe, 2012) to identify morphological, hydrological, and LW variables explaining wood piece displacement lengths.

In a last analytical step, we performed principal component analyses (PCA, Venables & Ripley, 2002) to identify morphological features that characterize channel reaches exhibiting high LW dynamics. Reaches were grouped into those exhibiting high versus low dynamics in terms of total number of wood pieces (1) entrained and transported from the reach to downstream reaches (mobility, MOB), (2) arriving from an upstream reach (deposition,

DEP), (3) repositioned (REP) within the reach, or (4) mobilized by the sum of the above types of motion (total dynamics, $DYN=MOB+DEP+REP$). Low versus high dynamics is evaluated relative to the mean value across all study reaches within a river (e.g., a high mobility-MOB reach in a specific study segment is one in which the total number of mobilized LW to downstream reaches is greater than the mean value of all reaches in this segment). Reach-average bankfull width and depth (w_{Bk} and d_{Bk} , m), longitudinal slope (S , $m \cdot m^{-1}$), stream power (SP , $W \cdot m^{-2}$, calculated from a simplification of the traditional equation following Rigon et al., 2012), LW volume (i.e., m^3 per km of reach length), and number of accumulations (N° per km of reach length) were included in the PCA. Information about reach LW volume and number of accumulations can be found in Iroumé et al. (2014, 2015). As in previous work (Iroumé et al., 2010), we defined accumulation when two or more wood pieces were in contact with each other.

We tested how LW displacement lengths differ according to different wood and reach variables (e.g., H_{max} , H_{Bk} , D_{LW} , L_{LW} , LW position in the channel, etc.) and how reaches characterized with high or low LW mobility differ in terms of morphological characteristics, using nonparametric tests; the Wilcoxon-Mann-Whitney (MW) test (rank sum test) for two independent samples or the Kruskal-Wallis (KW) test for more than two groups of tagged pieces. Statistical analyses were performed using R (R Core Team, 2013). Regressions and differences were considered for statistical significance at $p-values \leq 0.05$.

3 RESULTS

LW displacement length

The differences in displacement lengths between study periods and streams are summarized in Table 1.

Because we observed similar trends across each study site, we examine the ensemble data set in the subsequent analyses (Figure 2). Displacement lengths were longer during periods with $H_{\max} > H_{Bk}$ than in periods with $H_{\max} \leq H_{Bk}$ (Figure 2a), but differences are not statistically significant (non-parametric Mann-Whitney (MW) test, $p\text{-value} = 0.71$). Mean and median values of displacement lengths were 481 and 341 m when $H_{\max} > H_{Bk}$ ($n = 547$), and 304 and 175 m for periods with $H_{\max} \leq H_{Bk}$ ($n = 128$), respectively. Also, values of displacement distances corresponding to the 75th percentiles, largest values and extremes outliers are all longer when $H_{\max} > H_{Bk}$ than for periods with $H_{\max} \leq H_{Bk}$.

The above mentioned trend was especially significant for smaller wood pieces (i.e., with $D_{LW} \leq 40$ cm and $L_{LW} \leq 4$ m, $p\text{-values} < 0.05$, MW test, Figure 2b, c). For bigger pieces, displacement lengths were longer in periods with flows exceeding bankfull stage, but not in a statistically significant manner (MW, $p\text{-value} = 0.10$) for $D_{LW} > 40$ cm and only significantly (MW, $p\text{-value} = 0.04$) for $L_{LW} > 4$ m (Figure 2d, e); in these two analyses the values of displacement distances corresponding to the 75th percentiles, largest values and extremes outliers are all longer when $H_{\max} > H_{Bk}$ than for periods with $H_{\max} \leq H_{Bk}$. Displacement lengths were significantly longer (MW, results not shown) in periods with flows exceeding bankfull stage than in periods with flows lower than bankfull stage only for smaller normalized wood sizes ($D^* \leq 0.5$ and $L^* \leq 0.5$), but not for bigger normalized dimensions ($D^* > 0.5$ and $L^* > 0.5$).

Maximum displacement lengths (i.e. the maximum displacement length in every segment during each study period) were not significantly different (MW test, $p\text{-value} > 0.05$) among periods where maximum water level was higher and lower than the bankfull stage (Fig. 3a). For maximum displacement lengths, mean and median values were 696 and 818 m,

respectively, for periods with $H_{\max} \leq H_{Bk}$ ($n = 11$), and 897 and 804 m, respectively, during times where $H_{\max} > H_{Bk}$ ($n = 19$).

The data set is too small to compare independently for each study stream maximum displacement lengths among periods where maximum water level was higher and lower than the bankfull stage; we did not find meaningful relationships for each study segment and therefore combined the data. The only meaningful relationship found between displacement lengths of all entrained LW pieces for the different study periods, streams, and flow characteristics is the significant correlation ($p\text{-value} = 0.01$, MW) between maximum displacement lengths (i.e. the maximum displacement length of wood pieces in every segment) with $H_{15\%}$ (i.e., the level above which flow remains for 15% of the time during each study period; Figure 3b).

LW displacement lengths decreased with an increase of the ratio between LW piece diameter and length to $H_{15\%}$ (Fig. 4a, b). These trends are similar for all the study segments and statistically significant ($p\text{-value} = 0.00$) only for L_{LW} , thus explaining the variability of displacement lengths better. Indeed, maximum and median displacement lengths decrease as LW pieces become longer with respect to $H_{15\%}$; when analyzing these trends using the ensemble data set, values range from 2173 and 392 m for $L_{LW}/H_{15\%} < 10$ to 2012 and 259 m for $10 < L_{LW}/H_{15\%} < 25$, to 1300 and 229 m for $25 < L_{LW}/H_{15\%} < 50$, and to 1645 and 187 m for $L_{LW}/H_{15\%} > 50$ (Fig. 4c). Also, displacement lengths representing the largest values and the 75th percentiles decrease as LW pieces become longer with respect to $H_{15\%}$ (Fig. 4c); differences in displacement lengths are significant ($p\text{-value} = 0.00$, Kruskal-Wallis (KW) test) between $L_{LW}/H_{15\%}$ classes. The probability that LW pieces travel up to 50 m is relatively similar for all $L_{LW}/H_{15\%}$ classes (ranging from 79% for smaller to 65% for larger pieces), a

behavior which is similar up to displacement lengths of 150 m (Fig. 4d). However, the probability for LW pieces to travel more than 150 m is higher only for smaller wood pieces.

LW displacement lengths decreased with an increase in the ratio between LW piece length to reach bankfull channel width (i.e., L^*), a statistically non-significant ($p\text{-value} > 0.05$) trend that is similar for all the study segments (Fig. 5a). The analysis using the ensemble data set shows that maximum and median displacement lengths decrease as LW pieces become longer with respect to bankfull width, from 2173 and 345 m for $L^* < 0.25$, to 2085 and 305 m for $0.25 < L^* < 0.5$, and to 1987 and 228 m for $L^* > 0.5$ (Figure 5b). Displacement lengths are statistically different ($p\text{-value} = 0.04$, KW test) between the different L^* classes. The probability that a LW travels up to 50 m is relatively similar for all L^* classes (range from 80% for smaller to 70% for larger pieces), a behavior which is somehow similar up to displacement lengths of 150 m (Fig. 5c). However, the probability for a LW to travel over more than 150 m and especially more than 300 m reduces for larger wood pieces.

For each of the study segments, the type and the position of LW within the channel play a role in explaining LW displacement lengths. Analyzing the information using the combined data set, we found that unrooted logs travelled over significantly longer distances ($p\text{-value} = 0.01$, MW test) than logs with attached rootwads; median and maximum displacement lengths for the former are 316 and 2173 m, whereas the latter showed values of 31 and 986 m, respectively (Fig. 6a). Large wood pieces lying in the bankfull line travelled over significantly longer distances (with median and maximum displacement lengths of 556 and 1512 m, respectively) as compared to LW located in all other channel positions (Fig. 6b). LW located on the channel margins travelled less than those located in the bankfull channel and forming log-steps; in detail, the median value of displacement lengths for LW on the channel

margin is 159 m, whereas median lengths of 261 and 495 m were observed for LW located in the bankfull channel and in log-steps, respectively. However, displacement lengths are significantly different among LW located in each of the channel positions ($p\text{-value} < 0.05$, KW test).

Results from multiple regression analyses using log-link gamma generalized linear models (GLM) did not improve significantly the relationships described in the previous paragraphs between displacement lengths and individual flow and LW characteristics. Removing highly correlated variables, the statistically significant variables selected through the GLM analyses are L_{LW} , L_{LW}/H_{\max} , H_{Bk} , $H_{15\%}$, and LW species group and type (Table 2). However, the GLM model only explains 13.1% of the variability of displacement lengths, with $H_{15\%}$ explaining 8.6%, LW type an additional 2.2%, and the other variables explain the remaining 2.3% of total variability.

A few large logjams were broken during the period analyzed in this study, one in Pichún (2010) and one at Vuelta de Zorra (2011). A further large logjam was broken at the El Toro channel and is shown in Fig. 7. This logjam in fact built up between March 2009 and March 2010 and almost disappeared by December 2010. In all three cases, LW pieces from these broken logjams generally traveled over substantially shorter distances than LW pieces mobilized from other sources during the same periods and in the same segments (Table 3). Mean, median and maximum displacement lengths were shorter for LW from jams in Pichún and El Toro, while only maximum displacement length was shorter LW from jams in Vuelta de Zorra. However, the minimum displacement lengths of the LW originating from the breakage of logjams at all sites were clearly longer (i.e., between 1.2 and 59 times farther)

than the minimum displacement lengths of single wood pieces transported during the same years and within the same channel segments (Table 3).

Reaches exhibiting high LW dynamics

Our results clearly show that LW dynamics (entrainment, deposition and repositioning) are in general lower in Pichún and El Toro than in Tres Arroyos and Vuelta de Zorra (this stream showed the highest number of mobilized pieces, especially those transported downstream, during the study period). Also, we find that LW dynamics tend to be concentrated within a few reaches in each stream (Fig. 8), in terms of entrainment, deposition and repositioning.

At each of the study sites, most of the LW motion occurred as entrainment and transport downstream (MOB). The most downstream reaches (reaches 1-3) showed high LW dynamics in Pichún. El Toro shows a concentration of MOB in the more upstream (reaches 15-17) and middle (reaches 8-9) reaches, with LW deposition (DEP) mainly in the downstream and middle reaches (1, 2, 8). At Tres Arroyos MOB was concentrated in the more downstream reaches (reaches 3 to 10), with deposition (DEP) mainly in reaches 8 and 9 just downstream of reach 10, which shows the highest total MOB in this segment; repositioning (REP) occurred mostly in the upstream reaches. LW dynamics at Vuelta de Zorra, for MOB, DEP and REP occurred mainly in the middle and lower reaches of this study segment. In general, reaches with high LW deposition (DEP) also showed high LW repositioning (REP) and they were usually located downstream from reaches with high LW transport (MOB).

Different events seem to be responsible of LW dynamics, with mobility enhanced during specific years. As Figure 8 shows, during 2010 a large number of LW pieces were moved in El Toro and Pichún and during 2015 in Tres Arroyos, Vuelta de Zorra and Pichún. However,

these years are not characterized by substantial runoff events or large $H_{15\%}$ values, as can be seen in Table 1.

The PCA showed a clear differentiation between study sites for each type of motion discussed above (entrainment (MOB), deposition (DEP), repositioning (REP), and the total motion (dynamics, DYN) (Fig. 9).

For the combined data set, the PCA indicates that the most important variables explaining LW motion were: longitudinal slope (S), stream power (SP), bankfull depth (d_{Bk}) and bankfull width (w_{Bk}), with volume of stored LW (Vol_{LW}) playing a lesser role. The first two components of the PCA explained about 72% of the variance for the combined data and between 77 and 71% of the variance for each of the different mobility types, with the following relationships for all the sites combined:

$$PC1_{(DEP, high)} = -0.42 \cdot w_{Bk} - 0.1 \cdot d_{Bk} + 0.64 \cdot S + 0.45 \cdot SP + 0.43 \cdot Vol_{LW} \quad (1)$$

$$PC1_{(MOB, high)} = -0.35 \cdot w_{Bk} - 0.20 \cdot d_{Bk} + 0.66 \cdot S + 0.5 \cdot SP + 0.36 \cdot Vol_{LW} \quad (2)$$

$$PC1_{(REP, high)} = -0.05 \cdot w_{Bk} - 0.041 \cdot d_{Bk} + 0.64 \cdot S + 0.52 \cdot SP + 0.55 \cdot Vol_{LW} \quad (3)$$

$$PC1_{(DEP, low)} = -0.1 \cdot w_{Bk} + 0.30 \cdot d_{Bk} + 0.55 \cdot S + 0.65 \cdot SP + 0.41 \cdot Vol_{LW} \quad (4)$$

$$PC1_{(MOB, low)} = -0.26 \cdot w_{Bk} + 0.16 \cdot d_{Bk} + 0.61 \cdot S + 0.59 \cdot SP + 0.42 \cdot Vol_{LW} \quad (5)$$

$$PC1_{(REP, low)} = -0.50 \cdot w_{Bk} + 0.007 \cdot d_{Bk} + 0.63 \cdot S + 0.53 \cdot SP + 0.25 \cdot Vol_{LW} \quad (6)$$

$$PC2_{(DEP, high)} = -0.32 \cdot w_{Bk} - 0.74 \cdot d_{Bk} + 0.04 \cdot S - 0.56 \cdot SP + 0.15 \cdot Vol_{LW} \quad (7)$$

$$PC2_{(MOB, high)} = -0.46 \cdot w_{Bk} - 0.71 \cdot d_{Bk} - 0.007 \cdot S - 0.52 \cdot SP - 0.094 \cdot Vol_{LW} \quad (8)$$

$$PC2_{(REP, high)} = -0.5 \cdot w_{Bk} - 0.73 \cdot d_{Bk} + 0.07 \cdot S - 0.41 \cdot SP + 0.20 \cdot Vol_{LW} \quad (9)$$

$$PC2_{(DEP, low)} = -0.58 \cdot w_{Bk} - 0.67 \cdot d_{Bk} + 0.40 \cdot S - 0.20 \cdot SP + 0.11 \cdot Vol_{LW} \quad (10)$$

$$PC2_{(MOB, low)} = -0.53 \cdot w_{Bk} - 0.72 \cdot d_{Bk} + 0.24 \cdot S - 0.36 \cdot SP + 0.11 \cdot Vol_{LW} \quad (11)$$

$$PC2_{(REP, low)} = -0.42 \cdot w_{Bk} - 0.72 \cdot d_{Bk} + 0.16 \cdot S - 0.45 \cdot SP - 0.26 \cdot Vol_{LW} \quad (12)$$

In terms of total wood dynamics for all sites combined ($DYN = MOB + DEP + REP$):

$$PC1_{(DYNAMICS, high)} = -0.00048 \cdot w_{Bk} - 0.23 \cdot d_{Bk} - 0.60 \cdot S - 0.60 \cdot SP - 0.48 \cdot Vol_{LW} \quad (13)$$

$$PC1_{(DYNAMICS, low)} = 0.3 \cdot w_{Bk} - 0.08 \cdot d_{Bk} - 0.64 \cdot S - 0.58 \cdot SP - 0.40 \cdot Vol_{LW} \quad (14)$$

$$PC1_{(DYNAMICS, high and low)} = -0.3 \cdot w_{Bk} + 0.07 \cdot d_{Bk} + 0.6 \cdot S + 0.5 \cdot SP + 0.4 \cdot Vol_{LW} \quad (15)$$

$$PC2_{(DYNAMICS, high)} = -0.54 \cdot w_{Bk} - 0.68 \cdot d_{Bk} + 0.28 \cdot S - 0.26 \cdot SP + 0.32 \cdot Vol_{LW} \quad (16)$$

$$PC2_{(DYNAMICS, low)} = -0.50 \cdot w_{Bk} - 0.75 \cdot d_{Bk} + 0.19 \cdot S - 0.4 \cdot SP + 0.05 \cdot Vol_{LW} \quad (17)$$

$$PC2_{(DYNAMICS, high and low)} = -0.5 \cdot w_{Bk} - 0.74 \cdot d_{Bk} + 0.18 \cdot S - 0.4 \cdot SP + 0.05 \cdot Vol_{LW} \quad (18)$$

Here, PC1 is mainly related to the slope of the stream and the presence of obstacles (Vol_{LW}), illustrated by the vectors parallel to PC1 axe; while PC2 is mainly defined by the morphology of the stream (reach bankfull depth and width, d_{Bk} and w_{Bk} respectively are more parallel to PC2 axe). Stream power is more evenly split between the two (almost diagonal to both axes), as it is calculated using the slope and the bankfull width. In all biplots shown in Figure 9 the longitudinal slope and the Vol_{LW} are positively correlated, and both are negatively correlated with bankfull width. This means that steeper reaches, which are the narrower ones show high stored LW volumes.

When we grouped all reaches characterized with high and low dynamics ($DYN=MOB+DEP+REP$) for all streams, the PCA also resulted in a differentiation with the two groups slightly clustered in the biplot, although there is also a considerable overlap (Figure 10).

As Figure 10 shows, the morphology of the river (i.e., bankfull width and depth) is driving high LW dynamics, with the two vectors in the biplot pointing towards a majority of points characterized with high LW dynamics, and represented by positive values of PC1 and negative values of PC2. While, the slope of the river and the volume of stored LW are more important for the reaches characterized by low wood dynamics (the two vectors are directed towards the majority of points characterized with low LW dynamics mostly represented by

negative values of PC1 and positive values of PC2). In fact, we found statistically significant differences ($p\text{-value} < 0.05$, MW) between the two groups when analyzing the individual variables (Fig. 11).

As Figure 11 shows, we found significant differences in terms of bankfull depth, width, and stored wood volume between reaches characterized with high and low deposition (DEP; wood arriving from an upstream reach; Figures 11a, b, c). According to the PCA reaches with high LW deposition showed shallower channels (negative d_{BK} coefficients) and contained more wood than reaches with low deposition. This seems to contradict the results shown in Figure 11a, where the median value of the bankfull depth is lower for low deposition reaches (median d_{BK} for low deposition reaches is 0.98 m and 1.15 m for high deposition reaches).

However, the distribution was significantly different according to the MW test and the maximum and minimum values of bankfull depth are lower for reaches with high deposition (maximum d_{BK} for low deposition reaches is 2.49 m and 1.9 m for high deposition reaches; minimum d_{BK} for low deposition reaches is 0.7 m and 0.66 m for high deposition reaches). Reaches characterized with high DEP were less steep than reaches with low DEP, although differences were not significant (results are not shown in figure 11).

Stored wood volume was found important for wood repositioning (REP), with larger wood volumes in reaches characterized by high REP (Figure 11d). Reaches with high REP were in general less steep, shallower and wider than reaches with low REP, but differences were not significant (results not shown).

High entrainment (MOB) was recorded mostly in reaches characterized by lower slope, higher bankfull width and lower stored LW volume, although differences were not significant (results are not shown).

Stream slope and bankfull width seem to control the total mobility (Figs. 11e and f), with significantly lower slope and significantly wider channels exhibiting greater LW dynamics (DYN). Similar results were obtained for DEP, MOB and REP in terms of slope, although differences were not significant between reaches characterized by high and low mobility (results not shown here). In contrast, channel width was in general smaller for high deposition reaches, but differences were not significant.

4 DISCUSSION

In this study, we investigated LW dynamics and displacement lengths in four low-order streams of the Chilean Andes and the Coastal mountain ranges. The dataset used in this study (591 wood pieces measured, and 186 pieces tagged per km of channel) is based on more than 8 years of systematic monitoring in four streams, and exceeds the sample sizes suggested by Young et al. (2006) in terms of the number of LW pieces and reach lengths necessary to estimate wood piece dimensions and loads with a reasonable error. As such, we assume that our sampling is sufficient to be representative of the LW dynamics in our study reaches. Young et al. (2006) and Merten et al. (2010) tagged 250 and 206 wood pieces per km in Montana (USA) and Minnesota, respectively, and other similar studies used much lower numbers of tagged pieces, such as Berg et al. (1998) and Jacobson et al. (1999), who tagged 19 and 8 LW pieces per km in the Sierra Nevada (USA) and Namibia (Africa), respectively. Our results showed that LW displacement lengths were highly variable and differed substantially between individual pieces, different periods and also between the four streams analyzed (Table 1). LW displacement lengths reported here are in agreement with those previously reported by Martin & Benda (2001), who observed displacement lengths from about 200 m in small channels to greater than 1500 m in larger channels, although a bit lower than those observed in other low-order streams in the UK and USA, as reported by Millington

& Sear (2007), Keim et al., (2000), Dixon & Sear (2014), Berg et al., (1998) and Wohl & Goode (2008). This can be explained by the forest characteristics that supply LW pieces to these Chilean streams (long pieces relative to channel width and dense wood from native *Nothofagus spp.* and exotic *Eucalytus spp.*) and the hydrological regime during the study time (with no important floods, only flows with return periods ≤ 5 years; Iroumé et al., 2015).

LW displacement lengths were longer (although not statistically different) in periods for which $H_{\max} > H_{Bk}$ when compared with periods during which $H_{\max} \leq H_{Bk}$. These differences were statistically significant for smaller wood pieces but not for the larger LW; however, displacement distances for the tails of the larger wood distributions ($\geq 75^{\text{th}}$ percentile) were all longer when $H_{\max} > H_{Bk}$ than for periods with $H_{\max} \leq H_{Bk}$. In a similar way, maximum annual LW displacement lengths were not significantly different between periods with flows exceeding or remaining below the bankfull stage; however, from the distribution functions presented in Fig. 3a is possible to appreciate that transport distances corresponding to the 75^{th} percentile are higher for overbank flows. The overall lack of difference in transport lengths between high and low flows can be attributed to the presence of stable and recurring logjams which reduce LW displacement lengths as previously highlighted by Jacobson et al. (1999), Warren & Kraft (2008), Wohl & Goode (2008), Curran (2010) and Jochner et al. (2015).

As suggested by Ruiz-Villanueva et al. (2016b), not only peak flows, but the duration above which these flows remain during the year are important to explain LW displacement length. Therefore, we included the duration of flows in our analyses by calculating $H_{15\%}$. Our results showed that maximum displacement lengths of wood pieces were significantly correlated with the level above which the flow remains for 15% of the time (Figure 3). This means that LW pieces travelled longer distances only under certain hydraulic conditions, and when these conditions persisted for some time. If hydraulic conditions are not persistent, wood pieces might be rapidly deposited, even for higher peak discharges; for example, flashy hydrographs

may not be able to transport LW pieces longer distances than more flattened hydrographs (with longer times to peak) as pointed out by Ruiz-Villanueva et al., (2016b).

Prior studies generally have not included flow duration, which may explain why hydraulic variables, such as stream power, were not significant controls on wood mobility in those investigations (e.g., Lucia et al., 2015). However, more observations during floods are needed to suggest proper relationships (Wyżga et al., 2016).

While Abbe et al. (1993) and Braudrick & Grant (2000) reported a strong dependence of entrainment on LW piece diameter, general trends suggest that LW length is the key factor governing LW transport in single thread and narrow channels (Merten et al., 2010; Ruiz-Villanueva et al., 2016b; Welber et al., 2013), which are characteristic of our study segments. Our results support these prior studies, showing that L_{LW} best explains displacement length, which decreases as a function of LW length relative to both $H_{15\%}$ and reach bankfull width. Although median values of displacement lengths are not statistically different between different $L_{LW}/H_{15\%}$ and L^* classes, the values of displacement distances corresponding to outliers, maximum values and the 75th percentiles decrease as wood pieces become longer with respect to $H_{15\%}$ and w_{Bk} . The probability that a LW piece travels up to 150 m is relatively similar for all $L_{LW}/H_{15\%}$ and L^* classes, but the probability for a LW piece to travel over more than 150 m, and especially more than 300 m, clearly reduces for larger wood pieces. This coincides with findings from Gurnell et al. (2002), Wohl & Cadol (2011), Wohl (2011), Welber et al. (2013) and Bertoldi et al. (2014), among others, that larger pieces relative to bankfull channel are more stable and require higher flow depths to be entrained, thus influencing displacement distance.

LW displacement lengths could also be explained by LW type and LW position within the channel. Unrooted logs traveled over significantly longer distances than logs with attached rootwads, and thus confirm studies by Abbe & Montgomery (1996), Braudrick & Grant

(2000), and Cadol & Wohl (2010). Merten et al. (2010) further report that logs with attached rootwads and lengths exceeding the channel width are more stable than logs without rootwads. In our study reaches, results confirm that wood pieces located in the bankfull line travelled over significantly longer distances than LW located on the channel margins and in the bankfull channel; we attribute this finding to: a) the positive relation between maximum displacement length and $H_{15\%}$; b) the fact that wood pieces located in the bankfull line are transported only during near-bankfull and overbank flows; and c) because LW on the channel margins are blocked and trapped by riparian vegetation, thus restricting their entrainment. The distribution functions of displacement lengths for wood pieces located in the bankfull line and in the bankfull channel are clearly different; a higher median value and a much more normal distribution for the former, and a lower median value and a skewed distribution with a heavy tail toward longer distances for the latter. Although wood pieces located in the bankfull line travel over longer distances than LW located in the bankfull channel, they are in general more stable than the later (Iroumé et al., 2015) which coincides with findings by Schenk et al. (2014) who report that the majority of LW dynamics occur in the lower third of the channel. Using a multiple regression model we were able to explain only 13.1% of the variability of displacement lengths, with $H_{15\%}$ and LW type the principal descriptive variables. Other variables, such as the distance between logjams and the presence and frequency of steps (logs and boulders) were not explicitly considered in our study but might influence dynamics and should be taken into account in future research.. We found that the volume of stored wood also controls wood dynamics, with the volume of stored wood indirectly related to the distance between logjams. In addition, we acknowledge that measuring LW position once a year can conceal processes such as consecutive motion of individual pieces during subsequent floods within a given year, or prevent analysis of LW entrainment as a function of hydrograph shape and the number of floods. Therefore, multiple surveys per year, mainly

after floods, or additional monitoring approaches are highly recommended, especially in very dynamic streams. In this regard, active GPS, although very costly, provides the only method to track full LW trajectories, recording LW resting and movement periods (Ravazzolo et al., 2015).

Although pulses of transport occur when a logjam is broken (Wohl, 2011), LW pieces from three large logjams broken during the period of observation travelled over substantially shorter distances than other LW mobilized in the same periods and within the same segments. A logjam break could lead to congested transport then limiting transport distance and increasing wood deposition (Kramer & Wohl, 2016).

LW dynamics tend to be concentrated within a few reaches in each stream, in terms of transport downstream, deposition and repositioning. Reaches exhibiting high LW dynamics were significantly wider and less steep in the four analysed streams than reaches with low LW dynamics, thus confirming previous observations in the region and elsewhere (Iroumé et al., 2015; Ruiz-Villanueva et al., 2016d).

Wider channels are less restrictive to wood mobilization (Merten et al., 2010) and longer pieces can be moved during floods. At the same time, wider reaches may also have a tendency for generally shallower flow depths during the final phases of a flood, such that central and lateral sediment bars and stable wood pieces would be exposed rather quickly, thereby favouring deposition of the mobilized wood pieces (Ruiz-Villanueva et al., 2016a).

Although steeper reaches are expected to have higher wood mobility (as a result of higher stream power and energy), they also tend to be narrower than lower-gradient reaches, causing wood to more easily jam against banks and other obstructions, reducing the transport of LW (Ruiz-Villanueva et al., 2016d). This explains our findings from the PCA (i.e., channel slope was positively correlated with stored LW volume and negatively correlated with bankful width).

5 CONCLUSIONS

In this study we used a dataset collected in four mountain streams in Chile over more than 8 years using 1262 tagged wood pieces. Comparable datasets are scarce yet essential contributions to an improved understanding of large wood dynamics in small streams.

Although we recognize the complexity of such processes and illustrate some of the limitations, our results also highlight clearly that LW pieces travel longer distances during periods with flows exceeding bankfull stage for a given time, and that LW length is the main factor governing LW entrainment. In addition, we document that LW displacement lengths decrease for pieces that are large relative to $H_{15\%}$ and bankfull width. The unique dataset used in this work allowed us to show that the duration of flows is an important factor controlling LW mobility. Furthermore, we demonstrate that logs without roots and LW pieces located in the bankfull line travelled over significantly longer distances than logs with attached rootwads or LW located at other positions within the bankfull channel.

Finally, we observed that reaches exhibiting high LW dynamics show significant morphological differences compared to those with low LW dynamics, especially in terms of bankfull width and longitudinal slope. In addition, in-stream obstructions from stored wood volume plays an important role in controlling wood dynamics in the studied sites.

Our results confirm previous findings but also provide valuable insights on processes controlling LW dynamics in mountain rivers, and we believe they can be easily extrapolated to other streams in similar conditions. However, further observations, during longer time periods, different hydrological conditions and different morphological settings are needed to improve our knowledge about LW dynamics in rivers.

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Table 1. Range, mean, and median LW displacement lengths, number of transported wood pieces for different periods, channels, and flow conditions.

	Pichun								El Toro					Tres Arroyos								Vuelta de Zorra							
	Year								Year					Year								Year							
	2009	2010	2011	2012	2013	2014	2015	2016	2009	2010	2011	2012	2013	2009	2010	2011	2012	2013	2014	2015	2016	2009	2010	2011	2012	2013	2014	2015	2016
H_{\max}/H_{Bk} ¹	1.08	1.67	0.55	0.82	0.51	0.70	0.56	0.49	1.05	1.25	0.99	1.05	0.96	1.12	0.93	1.02	1.28	1.24	1.21	1.10	1.41	1.30	0.87	1.25	1.32	1.11	1.31	1.22	0.93
$H_{15\%}$	0.11	0.11	0.10	0.09	0.06	0.08	0.08	0.05	0.61	0.54	0.52	0.46	0.52	0.37	0.36	0.37	0.34	0.37	0.34	0.35	0.33	0.27	0.33	0.26	0.30	0.23	0.33	0.28	0.23
Range of displacement lengths (m)	6-142	10-251	0	27-27	0	0	8-986	7-818	10-1160	10-2173	19-1987	108-506	22-43	5-964	13-898	2-947	5-804	4-194	0.5-364	2-1894	6-2010	3-691	2-1536	2-1339	6-951	4-6	34-345	0.4-1536	1-1356
Mean and (median) of displacement lengths (m)	42 (7)	53 (31)	0	27 (27)	0	0	342 (190)	279 (253)	450 (375)	994 (911)	535 (119)	307 (307)	30 (24)	177 (15)	348 (134)	282 (10)	169 (39)	83 (67)	130 (48)	677 (724)	962 (913)	157 (93)	294 (33)	289 (124)	222 (78)	5.4 (5.5)	157 (120)	487 (453)	272 (218)
N° of LW, deposition	1	2	0	0	0	0	0	1	3	8	4	2	1	0	0	3	3	1	3	5	3	26	2	18	5	1	8	15	14
N° of LW, mobility	1	16	0	0	0	0	26	13	8	29	7	2	1	3	3	6	3	1	3	139	20	30	9	26	5	1	8	153	39
N° of LW, repositioned	4	3	0	1	0	0	1	2	1	1	2	0	2	8	0	7	3	3	3	2	3	14	12	11	3	4	1	10	10
Runoff (mm)	492	456	234	159	143	274	249	144	4100	2746	3717	2914	3529	2908	2228	2300	2267	2447	2356	2234	1801	3060	5524	3323	3865	2405	2750	2214	1570

¹ H_{max} is the maximum water level registered in the water level gauging station of each stream and study period; H_{Bk} is the bankfull depth in the cross section where the water level gauging stations are located.

Table. 2. Results from generalized linear model (GLM) (Numbers given in bold are statistically significant at $p\text{-value} \leq 0.05$). $H_{15\%}$ is the level above which the flow remains for 15% of the time during each of the periods analyzed.

Variable	Estimated Std.	Error	t value	p -value
	5.90774	0.47032	12.561	0.000
LW diameter (D_{LW})	-1.66827	1.24635	-1.339	0.181
LW length (L_{LW})	-0.01778	0.02267	-0.785	0.433
H_{\max}	0.14163	0.11717	1.209	0.227
L_{LW}/H_{\max}	0.07817	0.01954	4.001	0.000
H_{Bk}	-0.34846	0.41095	-0.848	0.397
D^*	1.6628	1.29045	1.289	0.198
$H_{15\%}$	3.45276	0.64795	5.329	0.000
$L_{LW}/H_{15\%}$	-0.01509	0.00629	-2.398	0.017
LW species group	-0.56376	0.1584	-3.559	0.000
LW position in the channel	0.07596	0.02572	2.953	0.003
LW type	-0.22315	0.07845	-2.844	0.004

Table 3. Comparison of displacement lengths for log-forming jams or representing single elements. Period 2010 for Pichun and El Toro and 2011 for Vuelta de Zorra.

Displacement length	Pichun		El Toro		Vuelta de Zorra	
	Jam	Single	Jam	Single	Jam	Single
Mean (m)	24	71	728	1104	299	210
Median (m)	31	40	728	1089	206	16
Minimum (m)	12	10	539	10	118	2
Maximum (m)	32	252	916	2173	622	903

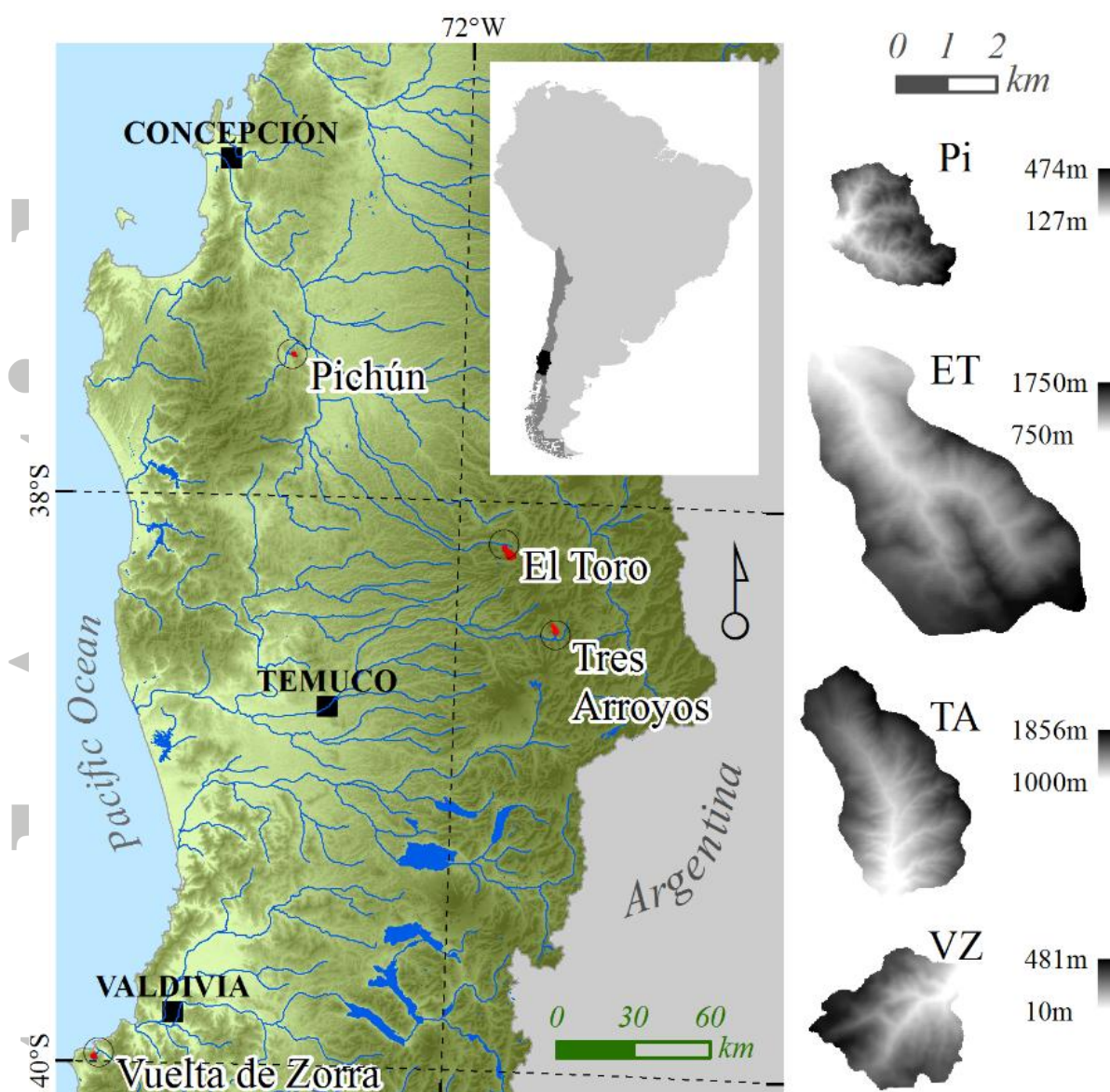


Figure 1. Location of the study sites. Circles correspond to the locations of the catchment outlets. Digital elevation model of the catchments are shown to the right. Pi: Pichún; ET: El Toro; TA: Tres Arroyos; VA: Vuelta de Zorra.

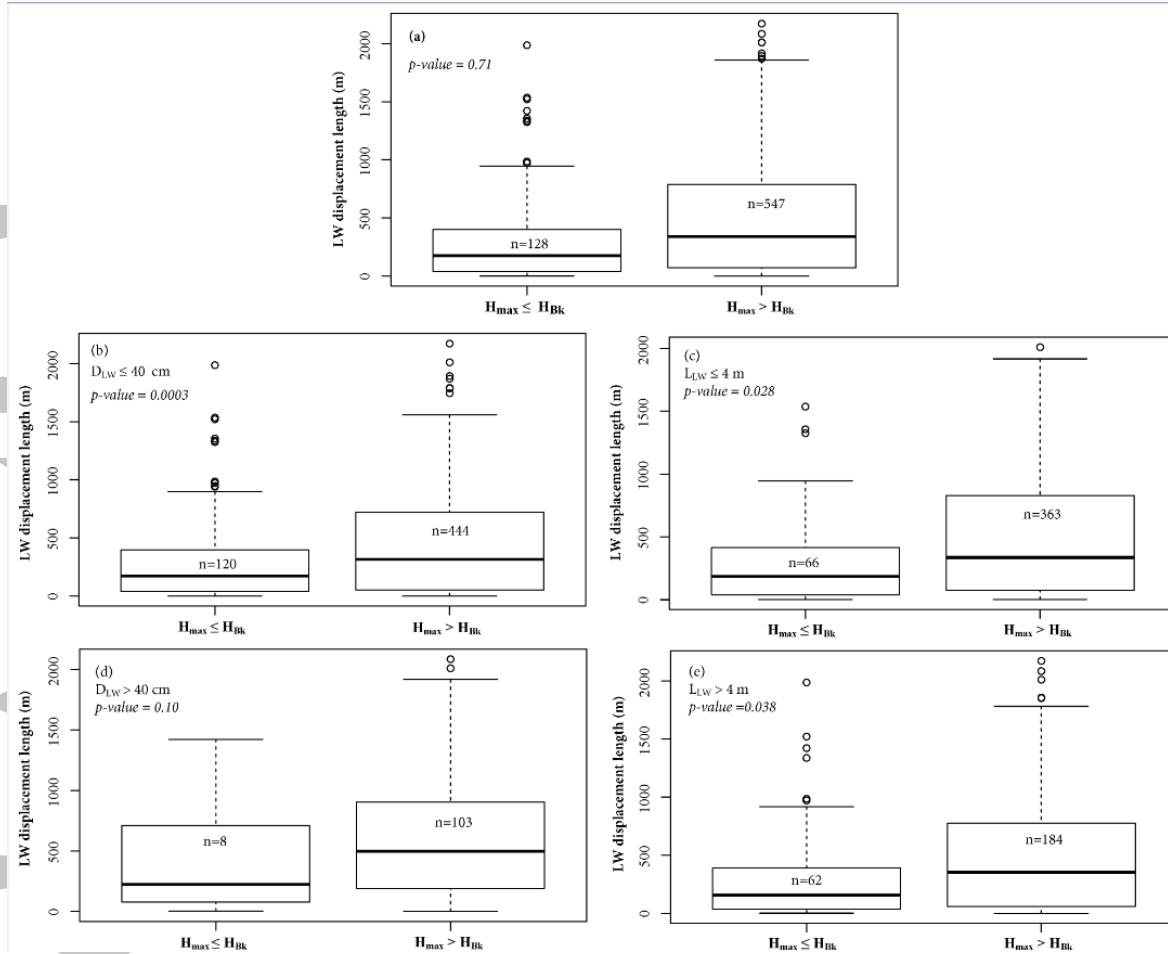


Figure 2. Box-plots of individual LW displacement lengths for $H_{\max} \leq H_{Bk}$ and $H_{\max} > H_{Bk}$ for: (a) all LW pieces; (b) LW with dimensions $D_{LW} \leq 40$ cm; (c) with $L_{LW} \leq 4$ m; (d) $D_{LW} > 40$ cm; and (e) $L_{LW} > 4$ m. The line within each box indicates the median value, box ends are the 25th and 75th percentiles, and the whiskers show the largest value within 1.5*interquartile range from third quartile and the minimum value, whereas circles are the outliers. In a), b), c) and d), $p\text{-values}$ using Mann-Whitney non-parametric test.

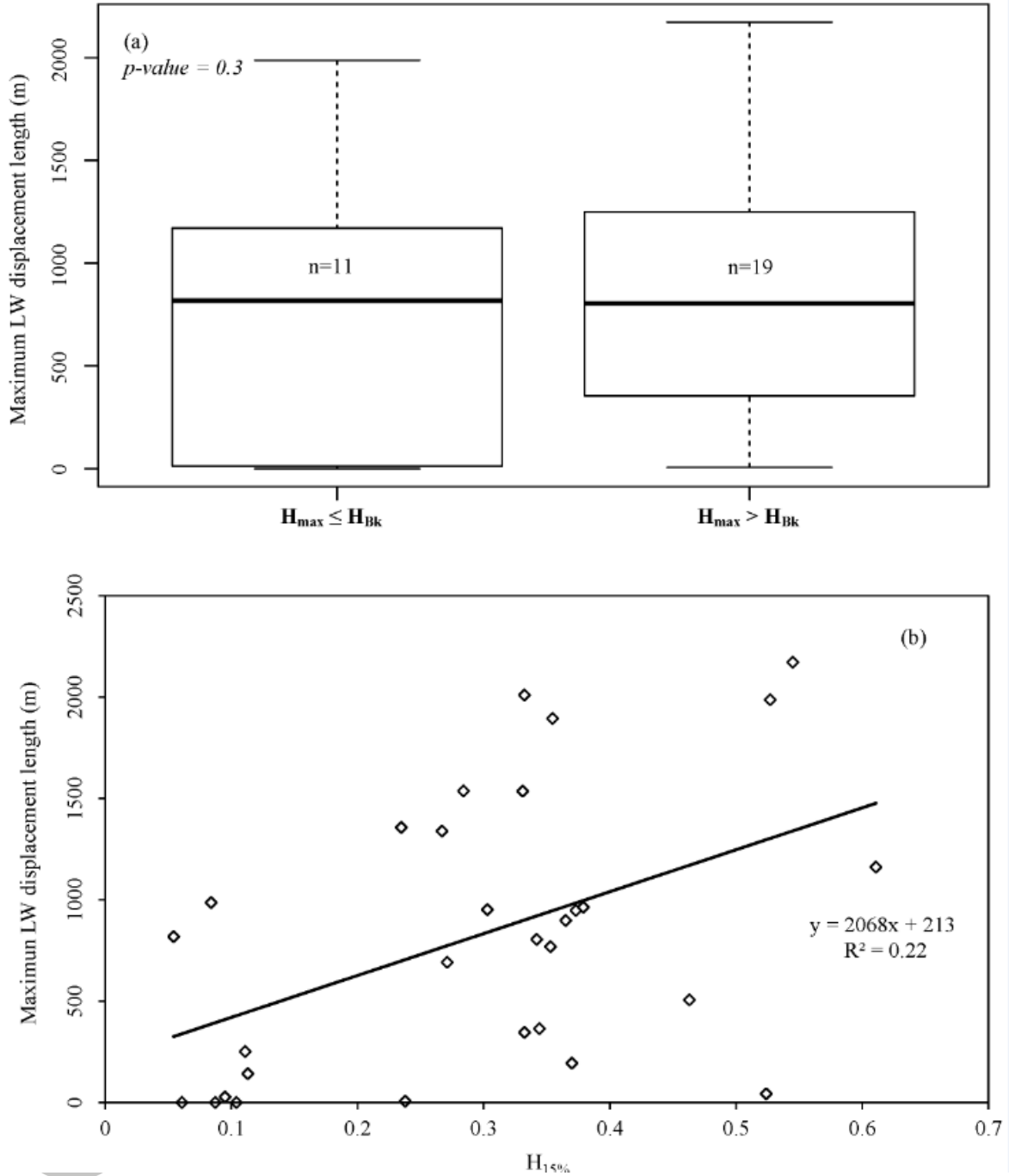


Figure 3. (a) Box-plots of maximum LW displacement lengths for $H_{\max} \leq H_{Bk}$ ($n = 11$) and $H_{\max} > H_{Bk}$ ($n = 19$); for box-plot definitions see Fig. 2; (b) relationship between maximum LW displacement length and $H_{15\%}$. H_{\max} , H_{Bk} and $H_{15\%}$ are in m. In (a), p -value using Mann-Whitney non-parametric test.

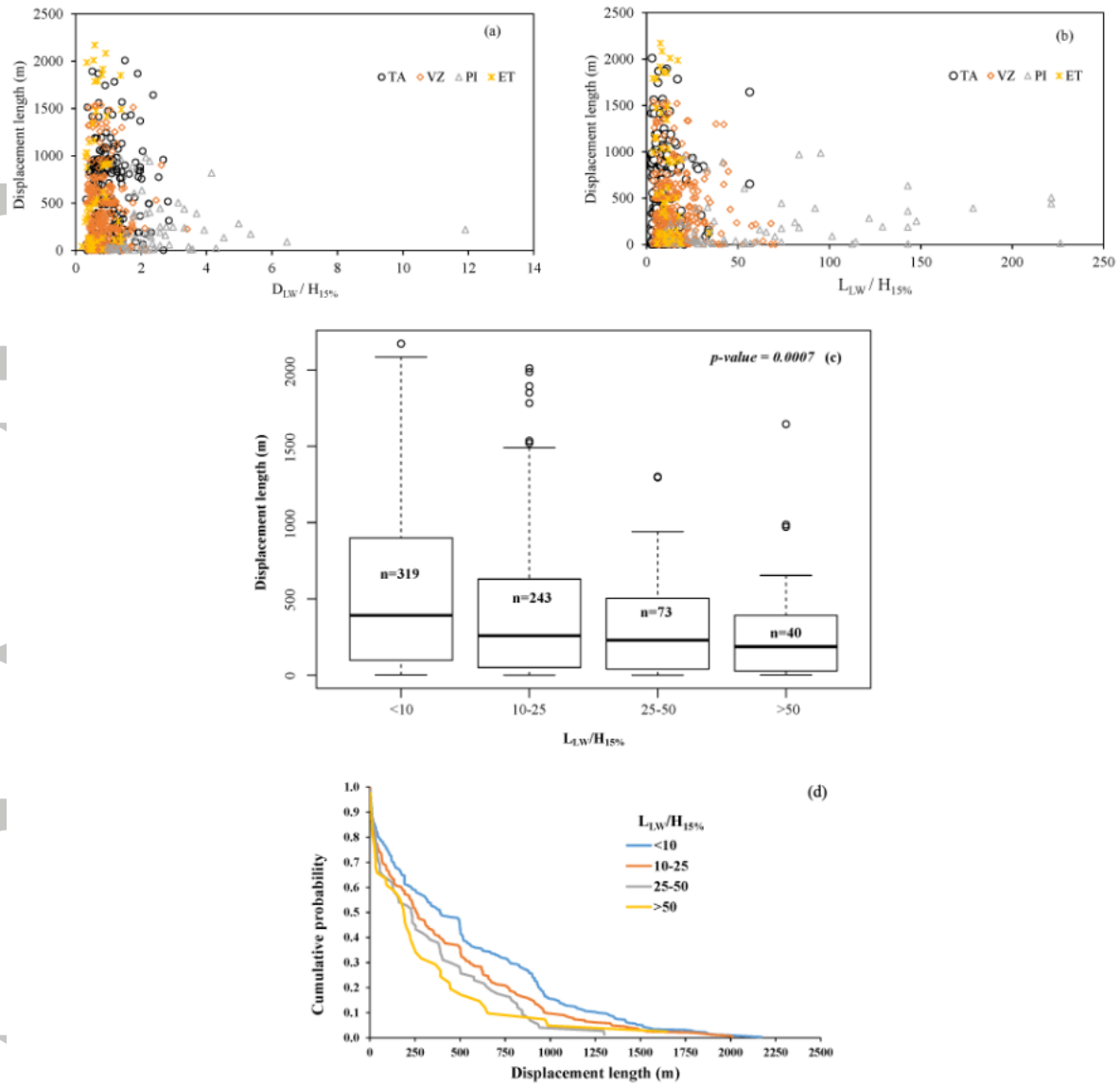


Figure 4. Relationships between LW displacement lengths (m) with: (a) piece diameter/ $H_{15\%}$, and (b) piece length/ $H_{15\%}$; (c) box-plots of LW displacement lengths (m) for $L_{LW}/H_{15\%} < 10$, 10-25, 25-50 and > 50 (for box-plot definitions see Fig. 2); and (d) cumulative probability of displacement lengths for the different $L_{LW}/H_{15\%}$ ranges. In (c) *p-value* using Kruskal-Wallis non-parametric test.

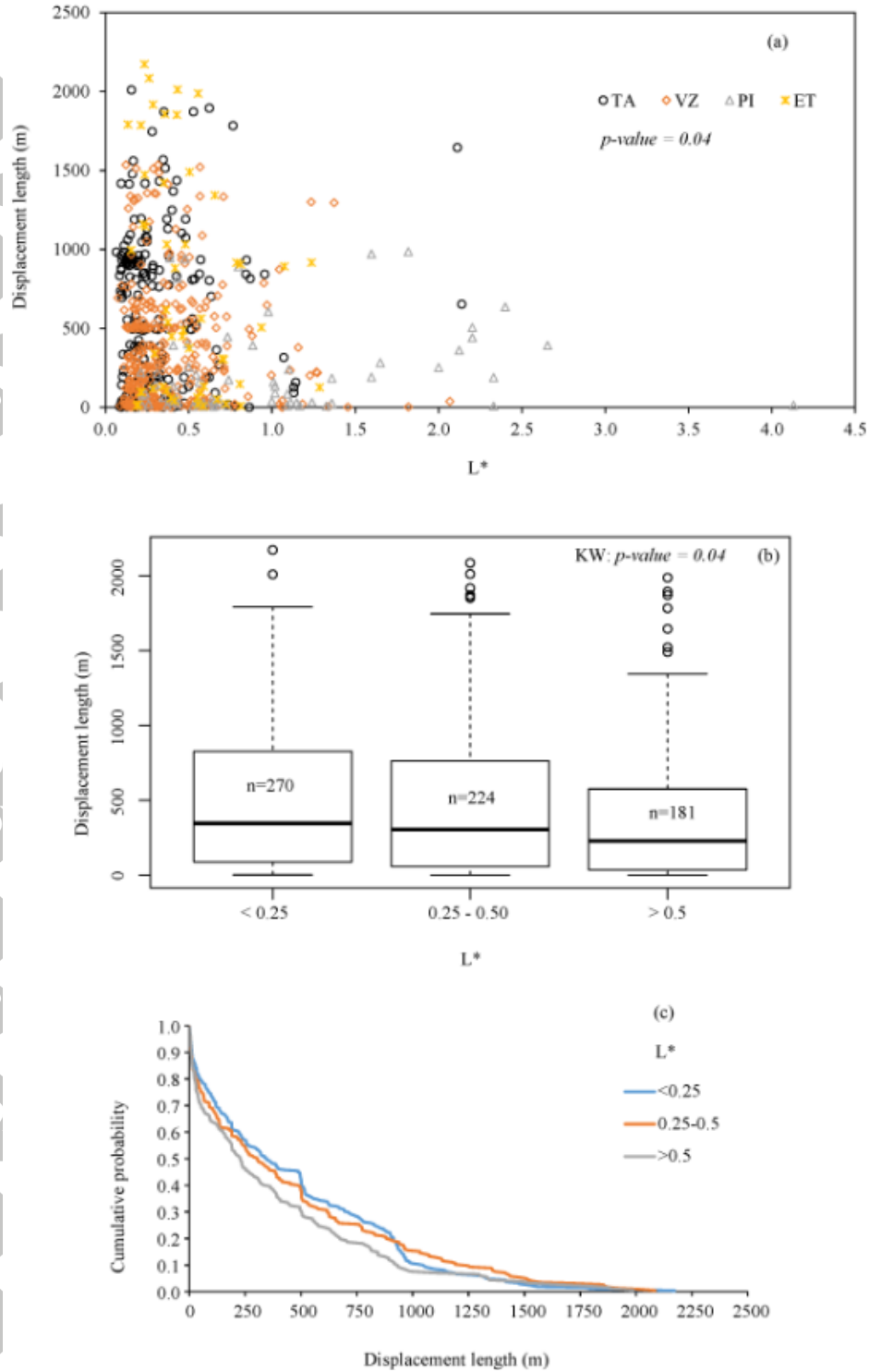


Figure 5. (a) Relationship between LW displacement lengths and piece length/bankfull width (L_{LW}/w_{BK} or L^*); (b) Box-plots of displacement lengths (m) for $L^* < 0.25$, $0.25 - 0.50$ and > 0.50 (for box-plot definitions see Fig. 2); and (c) cumulative probability of displacement lengths for the different L^* ranges. In (b) $p\text{-value}$ using Kruskal-Wallis non-parametric test.

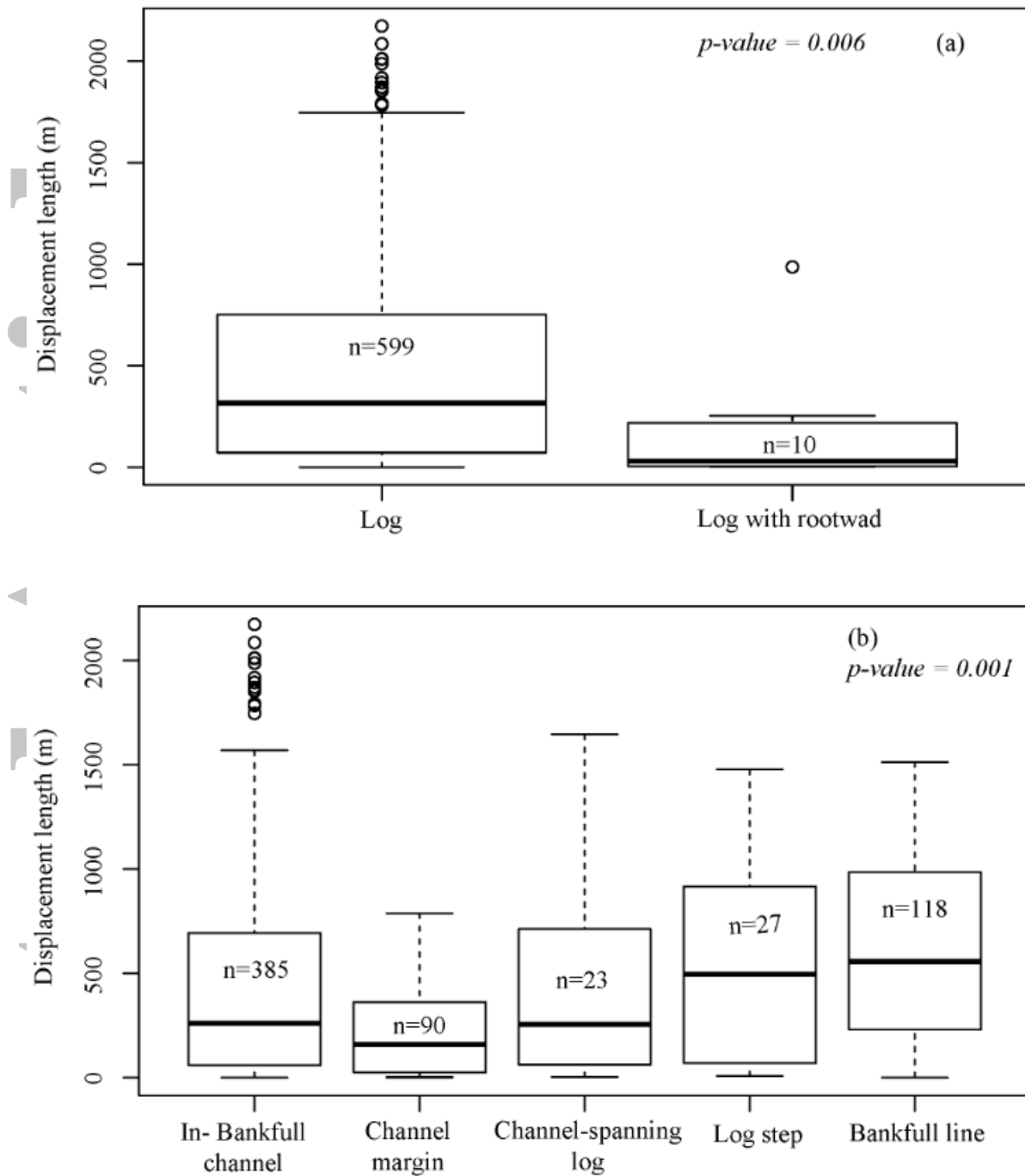


Figure 6. Box-plots of LW displacement lengths (m) for: (a) log type; and (b) LW position in the channel (for box-plot definitions see Fig. 2). In (a) and (b) *p-values* using Mann-Whitney and Kruskal-Wallis non-parametric tests, respectively.



Figure 7. Formation and destruction of a logjam at El Toro stream; photos facing downstream (white arrows show flow direction) from (a) March 2009; (b) March 2010; and (c) December 2010. The person shown in photo (b) is 1.73 m tall and gives an idea of the channel and LW dimensions; the tree indicated by a red arrow is the same in all photos. The effect of the logjam on the sediment accumulation can be observed in pictures (a) and (b).

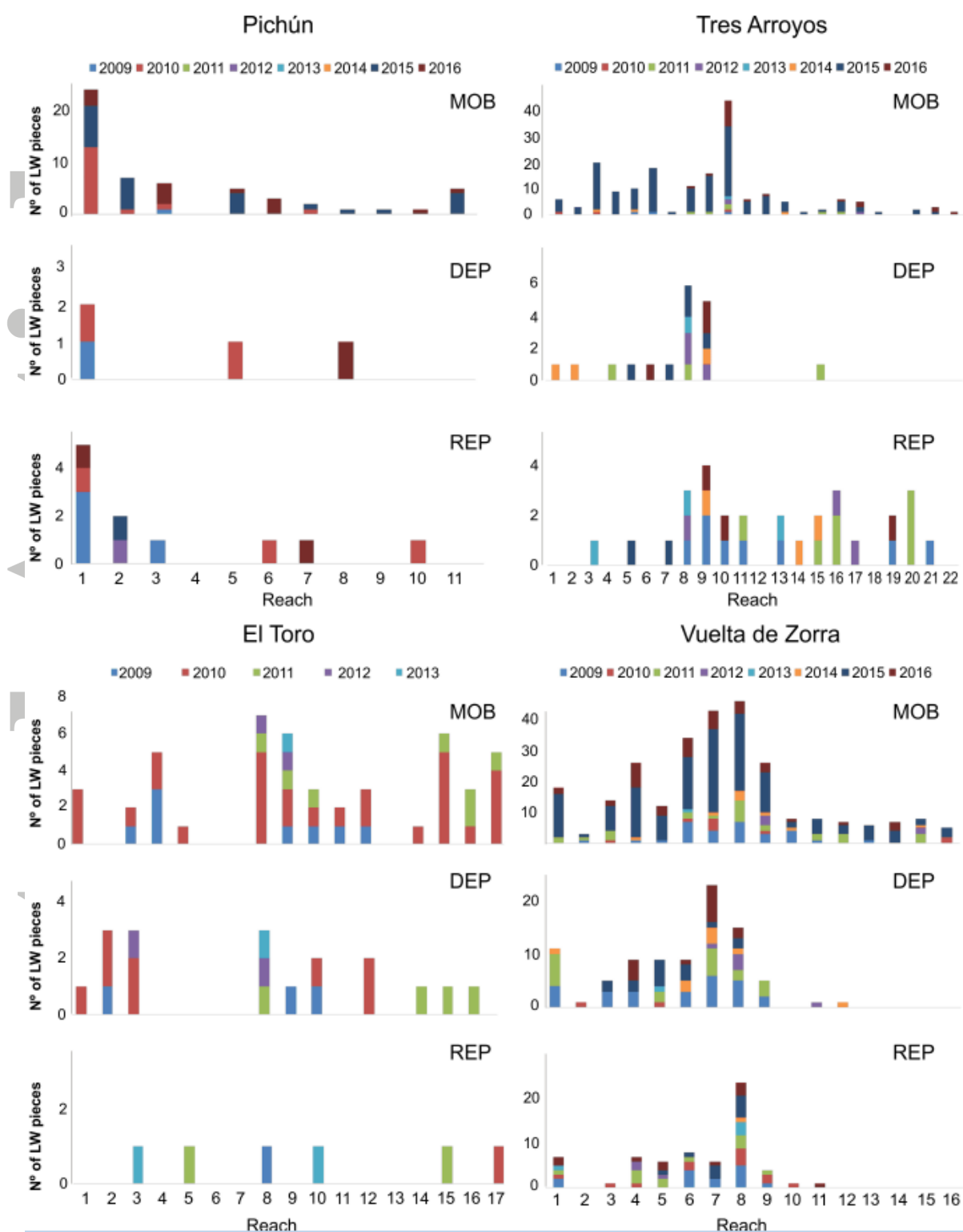


Figure 8. Number of mobilized (MOB), deposited (DEP) and repositioned (REP) LW in all study segments and during each study time period and reach. Reaches are numbered from downstream to upstream.

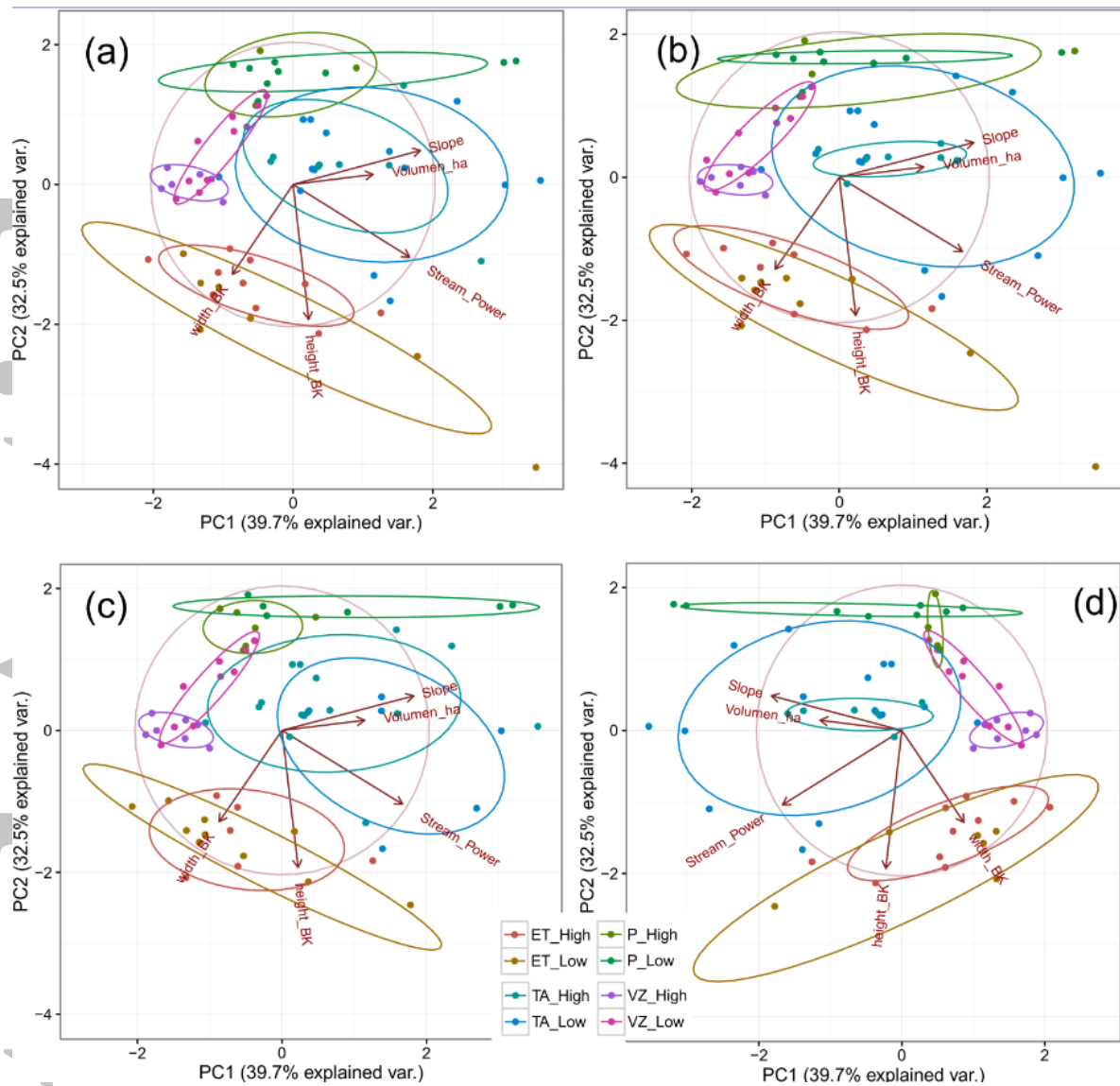


Figure 9. Biplots showing the loadings of channel variables (stream power, slope, volume of stored wood, bankfull width and depth) on the PC1 and PC2 axes for data stratified by study site (ET: El Toro; TA: Tres arroyos; P: Pichún; VZ: Vuelta de Zorra), high vs. low LW mobility, and type of LW motion: (a) LW input arriving from an upstream reach (DEP); (b) entrainment and transport to downstream reaches (MOB); (c) repositioned within the reach (REP); and (d) total LW dynamics (DYN = MOB+DEP+REP).

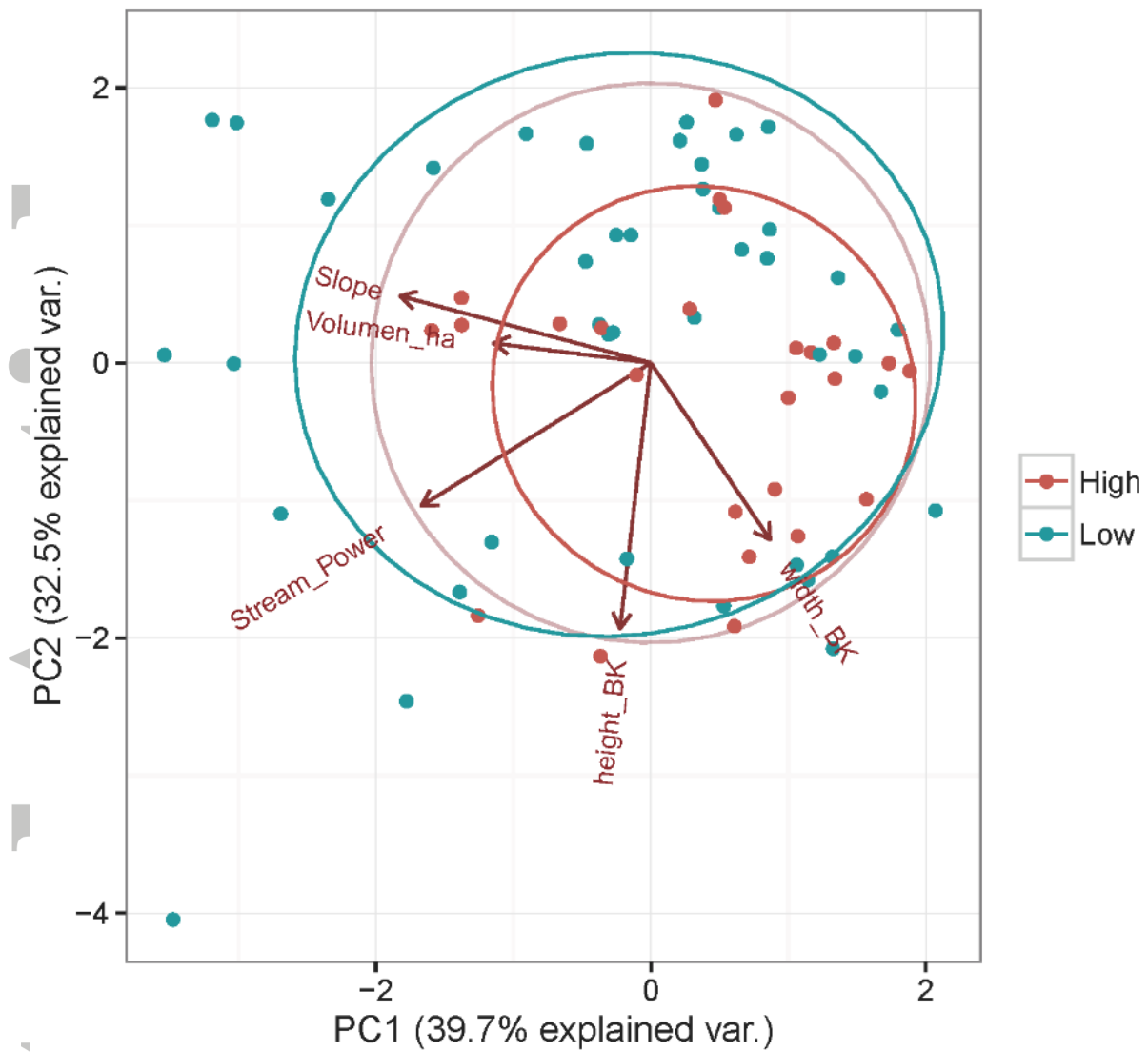


Figure 10. Biplots showing the loadings of channel variables (stream power, slope, volume of stored wood, bankfull width and depth) on the PC1 and PC2 axes for all data stratified by high and low values of total LW dynamics (total number of wood pieces transported to downstream reaches, arriving from an upstream reach and re-positioned within the reach).

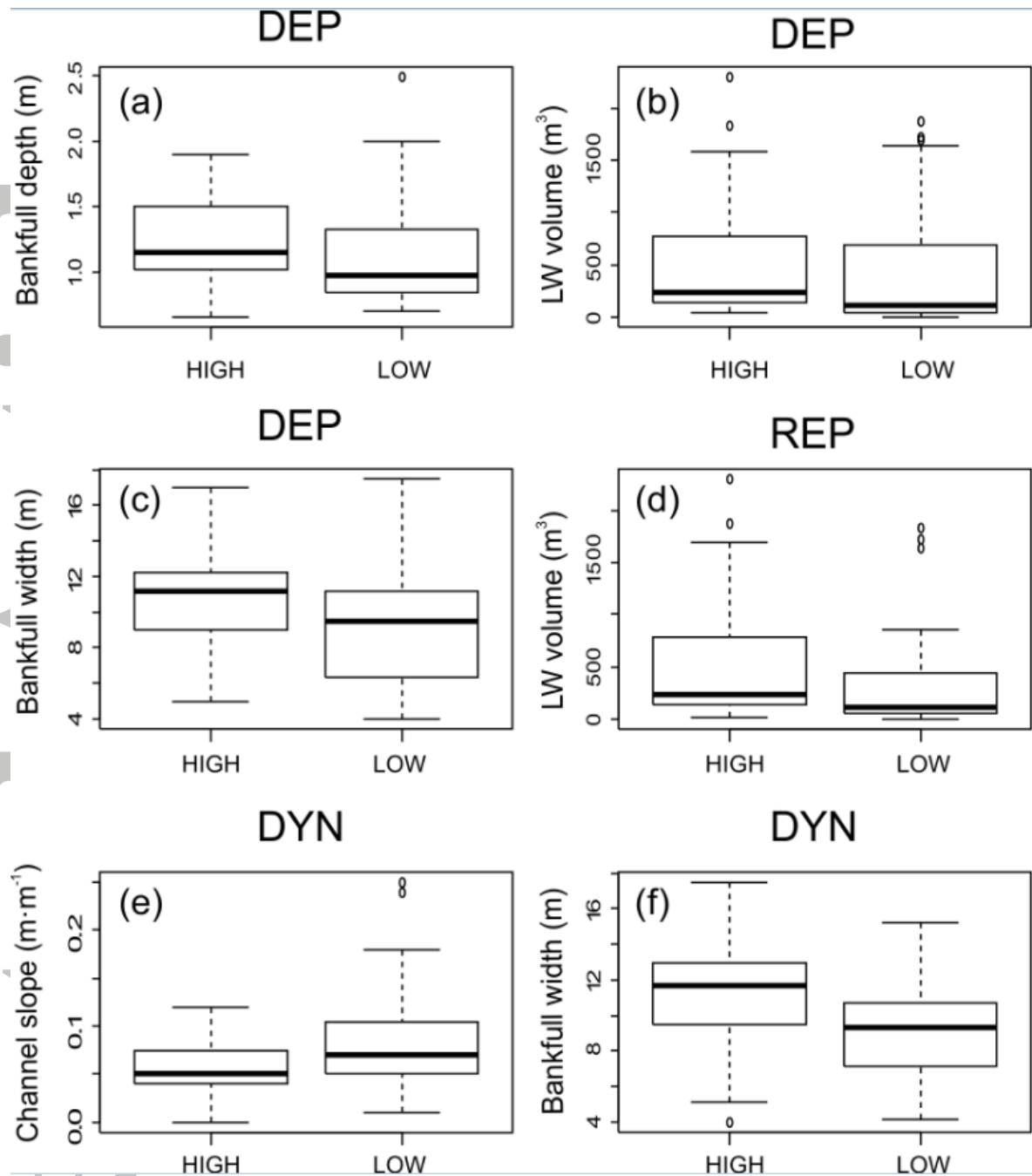


Figure 11. Boxplots (for box-plot definitions see Fig. 2) of significantly different morphological characteristics (p -value < 0.05 , non-parametric MW test) that distinguish reaches having high versus low values of (a)-(c) LW deposition (DEP: wood arriving from an upstream reach), (d) repositioning (REP: re-positioned wood within the reach) and (e)-(f) total wood mobility (DYN=DEP+REP+MOB (wood entrained from the reach and transported downstream). All values are reach averages.